The Influence of Driver Power and Receptor Confinement on Pre-detonators for Pulse Detonation Engines

S.B. Murray, F. Zhang, and K.B. Gerrard
Defence Research Establishment Suffield
Box 4000, Station Main, Medicine Hat, Alberta, Canada T1A 8K6
Stephen.Murray@dres.dnd.ca

INTRODUCTION

There has recently been considerable interest in the concept of pulse detonation engines (PDEs). From a practical perspective, it is highly desirable that PDEs use combustible fuels which have already been approved by the aviation industry (e.g., JP-10 or Jet-A). One drawback to the use of these fuels in PDEs is that the resulting fuel-air mixtures are relatively difficult to detonate.

Direct initiation of detonation by a powerful electrical igniter would be impractical for a PDE employing aviation fuels. Akbar et al. [1] have recently reported that the detonation cell size for stoichiometric JP-10 vapour and air at atmospheric pressure and a temperature of 135 ^{o}C is about 5 cm. This cell size indicates that JP-10/air is approximately equal in sensitivity to propane-air [2] which has a critical charge mass for spherical initiation of about 50 grams of tetryl [3]. Weak ignition followed by deflagration-to-detonation transition (DDT) would not appear to be a practical option for JP-10/air either. The recent work of Higgins et al. [4], for example, has shown that the transition distance for stoichiometric propane-air in a 15-cm diameter closed tube, fitted the full length with DDT-enhancing obstacles, is on the order of a few metres. It has also been shown that combustible mixtures, once formed, can be further sensitized by injecting halogens or hot free radicals. However, considerable work would have to be done before these methods could be implemented in a practical PDE.

One initiation scheme receiving considerable attention within the PDE community involves the use of a "pre-detonator" or "driver" tube [5]. In this concept, a detonation is first formed in a sensitive fuel-oxygen mixture by spark ignition followed by rapid DDT. The established wave is then used to initiate the less sensitive fuel-air mixture contained in the main combustion chamber. It is desirable from both safety and performance points of view to keep the volume of the pre-detonator as small as possible. Accordingly, the diameter of any practical pre-detonator will be considerably smaller than that of the main combustion chamber. Therefore, the efficiency of transmission from the driver to the main chamber will be an important issue.

In a previous paper [6], it was shown that transmission of detonation from a tube to a larger vessel can be enhanced by installing a central circular blockage at the tube exit or by introducing a reflecting boundary in the path of the emerging wave. Both geometries lead to strong shock reflections and localized explosion centres which are capable of sustaining the wave during its global expansion downstream of the tube exit. In the present paper, the transmission of detonation from a fuel-oxygen driver to a larger, co-axially aligned receptor tube containing fuel-air mixture is investigated. The objectives of this study are: (i) to quantify the effectiveness of a fuel-oxygen detonation at initiating unconfined fuel-air detonations, and (ii) to quantify the degree to which confinement offered by the side walls of the receptor tube is able to enhance the transmission process. Almost no information has been published about this fundamental problem despite its obvious importance in the design of PDEs based on the pre-detonator concept.

NUMERICAL SIMULATIONS

Numerical simulations have been carried out to illustrate the salient features of the shock reflection and reinitiation processes in the geometry of current interest. The calculations were two-dimensional, axisymmetric in nature, and were performed using a second-order Godunov-type explicit scheme implemented in the IFSAS code [7]. The driver and receptor tubes, having diameters of D_0 and D, respectively, contained the same combustible mixture for the purposes of this simulation. A simple, one-step, Arrhenius reaction scheme was employed. The computations were performed assuming a constant specific heat ratio $\gamma = 1.4$ and a heat release corresponding to a Mach number $M_{CJ} = 5$, which is typical for fuel-air mixtures. Detonation was initiated at the beginning of the driver which was open ended to avoid reflected shocks.

Results of the simulations are shown in Figure 1. The transmission of detonation from one tube to the other begins with the usual diffraction process characterized by a decoupling between the diffracted portion of the shock wave and its corresponding reaction zone. Time t=0 denotes the moment of imminent reflection of the diffracted wave from the receptor tube walls. Providing that the ratio D/D_0 is relatively small (Fig. 1a), the diffracted shock is sufficiently strong to reinitiate detonation a short time after reflecting from the side walls. The reinitiated wave initially takes the form of an annular fully reacting bubble. The latter evolves into an overdriven detonative Mach stem which expands ahead of the neighbouring incident wave which, by this time, has completely decoupled itself from the trailing reaction zone. The wave ultimately becomes self-sustained as it decelerates to the Chapman-Jouguet velocity. If the area increase at the expansion is too large, the reflected wave will be too weak to reinitiate detonation directly and transmission will fail (Fig. 1b). The volume and life time of the region of high energy density associated with the reflection and Mach stem are too small to allow sufficient energy release to maintain the strength of the reacting bubble. Accordingly, for a given set of driver and receptor initial conditions, some critical value of D/D_0 will exist for which transmission is just possible. Of course, for $D >> D_0$, the side walls do not play any role in the transmission process and the critical conditions would be identical to those for transmission to an unconfined region. It is possible that both the spontaneous mode of reinitiation observed near the head of the expansion in the unconfined case and the reflected mode near the wall in the confined case could occur simultaneously for an appropriate combination of mixture sensitivity and D/D_0. Alternatively, it might be possible for the cylindrically imploding reflected shock to cause reinitiation near the tube axis even though it was too weak to cause reinitiation near the wall.

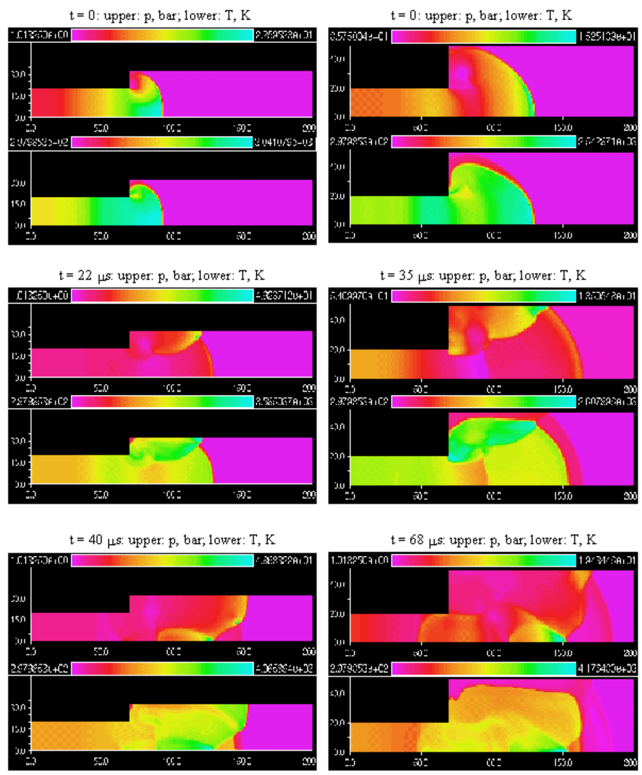

Figure 1. Pressure and temperature profiles from numerical computations showing successful transmission of detonation and failure to transmit from a driver to a receptor tube. D_0 = 4 cm, γ = 1.4, M_w = 28.8 g/mole, Q = 1.445 MJ/kg, E = 4.30 MJ/kg, k = 3 x 10^9 sec^{-1}, cell = 1 x 1 mm^2. (a)-Left: D/D_0 = 1.6 (successful transmission). (b)-Right: D/D_0 = 2.5 (failure).

It should be noted that the above-described calculations remain strictly qualitative in nature due to the assumptions involved in the reaction model. This is particularly true considering that the grid resolution is insufficiently fine to properly resolve the ZND structure of the detonation front or the finer details of the shock reflection process. Furthermore, it is too coarse to take into account the cellular structure of the detonation or many of the high-frequency instabilities which can play an important role in the onset of detonation. Indeed, owing to the three-dimensionality of the cellular detonation front, a complete and exact modelling of the transmission process remains difficult at the present time. Consequently, the quantitative evaluation of the critical conditions must be done experimentally.

EXPERIMENTAL RESULTS

Two sets of experiments were conducted. The first series was intended to determine the effectiveness of using a fuel-oxygen driver to initiate an unconfined fuel-air detonation, versus the use of a fuel-air driver. The apparatus, shown in Figure 2, consisted of a steel driver tube of either 5.08 cm or 7.62 cm inside diameter connected to a plastic bag measuring 1 metre in diameter by approximately 3 metres long. Each driver was 20 diameters in length and fitted with two pressure transducers located near the tube exit. Tests were done for both stoichiometric and equimolar acetylene-oxygen driver gases. These were prepared in a cylinder by the method of partial pressures one day prior to testing. At least five volumes of C_2H_2-O_2 mixture were flushed through the driver tube during filling. The mixture was spark ignited at the closed end and consistently underwent rapid DDT as verified by the measured detonation pressures and velocities. The sensitivity of the acetylene-air mixture in the bag was controlled by adjusting the stoichiometry. A pre-calibrated Wilks Miran infrared analyzer was used for this purpose. A polyethylene diaphragm 0.04 mm thick was used to separate the fuel-oxygen and fuel-air mixtures. Smoke foils were mounted on the wall surrounding the tube exit and on a horizontal plate at the far end of the bag. These were used to indicate success or failure of detonation in the bag and to confirm the mixture composition and homogeneity. A side-on, high-speed, video camera framing at 1000 pictures per second was also used to monitor the event. The early motion of the diaphragm has been calculated using the approximate analytical model proposed by Meyer [8]. Based on these calculations, the authors believe that the presence of the diaphragm has a negligible effect on the results.

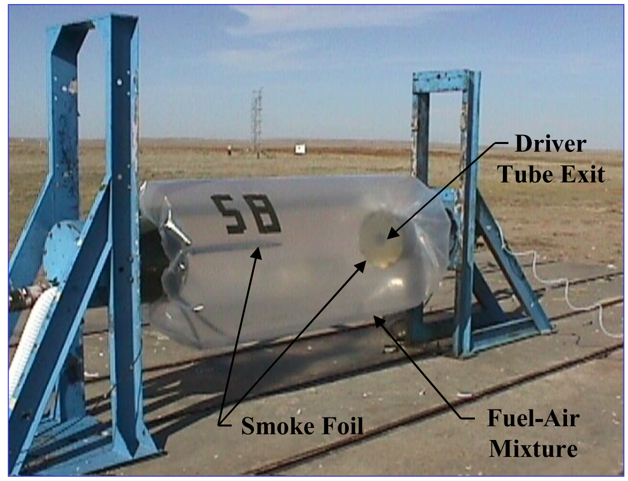

Figure 2. Experimental setup used to determine the critical conditions for transmission from a fuel-oxygen driver to an unconfined fuel-air receptor gas.

The test results are summarized in Table I where it can be seen that the stoichiometric C_2H_2-O_2 mixture was incapable of initiating a detonation in stoichiometric C_2H_2-air for both driver tubes. However, when the stoichiometric fuel-oxygen mixture in the larger driver was replaced by an equimolar mixture, successful transmission did indeed occur. In fact, transmission continued to be possible as the C_2H_2-air mixture was made increasingly leaner. The critical acetylene concentration was found to be 6.13 ± 0.13%. Successful initiation with an equimolar fuel-oxygen driver versus a stoichiometric one is likely attributable to the substantially higher detonation velocity of the equimolar mixture (i.e., 2937 m/s versus 2425 m/s for stoichiometric at P = 1 atm and T = 300 ^{o}K), and hence the stronger shock wave transmitted to the fuel-air mixture.

Note that the sensitivity of the driver mixture is not likely an important parameter in the transmission process. The critical tube diameters for equimolar and stoichiometric acetylene-oxygen at atmospheric pressure are estimated to be 1 and 1.3 mm, respectively, based on the correlations of Matsui and Lee [9]. The latter diameter is somewhat smaller than the 2.5 mm (at P_0 = 800 torr) reported by Zeldovich *et al.* [10]. In any event, the driver tubes used in the present work exceed the critical tube diameters for the acetylene-oxygen mixtures by a factor of at least 20 to 50.

From a fundamental perspective, this initiation scenario is somewhat different from the usual case of transmission from a tube to an unconfined region in a uniform combustible mixture. In the critical tube problem, the planar detonation wave emerging from the tube is attenuated by the inward propagating rarefaction wave. Under critical conditions, the expansion becomes mild enough for reinitiation to occur just prior to the unattenuated core of the wave being completely quenched. It has been proposed by Lee and Matsui [11] that the critical energy can be approximated by the work done by the interface separating the expanding combustion products and the unconfined combustible

Table I
Pre-detonator Trials: Acetylene-Oxygen Initiating Unconfined Acetylene-Air

Trial Number	**Driver Tube Diameter (cm)**	**Driver Gas C_2H_2-O_2**	**Receptor Gas %C_2H_2-air**	**Result**	**Driver Tube Effectiveness $\beta_1 = d_c/D_0$**
52-00	5.08	Stoichiometric	7.75	Failure	-
55-00	7.62	Stoichiometric	7.75	Failure	-
54-00	7.62	Equimolar	7.75	Detonation	1.51
56-00	7.62	Equimolar	6.75	Detonation	2.34
57-00	7.62	Equimolar	6.25	Detonation	3.10
59-00	7.62	Equimolar	6.00	Failure	(3.64)
58-00	7.62	Equimolar	5.75	Failure	-

mixture. More recently, the work done by the lateral interfaces outside the detonation core has also been accounted for in the theory [12]. In the case of a powerful fuel-oxygen driver, a shock wave is first transmitted from the tube to the fuel-air mixture. Again, a rarefaction wave propagates inward from the sides. However, owing to the considerably higher detonation velocity of the fuel-oxygen mixture, the strength of the transmitted shock remains considerably above the Chapman-Jouguet shock strength for the fuel-air mixture well after the rarefaction has penetrated to the tube axis. Under critical conditions, the wave likely decelerates to the Chapman-Jouguet velocity, $V_{C\text{-}J}$, in the fuel-air mixture by the time it reaches the radius at which reinitiation would typically take place in the more usual critical tube problem (i.e., fuel-air to fuel-air). One could probably further modify the work done model to account for this overdriven wave which decelerates from $V_{C\text{-}J}$ in the fuel-oxygen mixture to $V_{C\text{-}J}$ in the fuel-air mixture. In fact, given that initiation of the fuel-air detonation is characterized by a powerful decaying blast wave, the fuel-oxygen driver may more appropriately be mimicking a high-explosive charge under conditions of direct initiation. Thus, an explosion length model might also be appropriate.

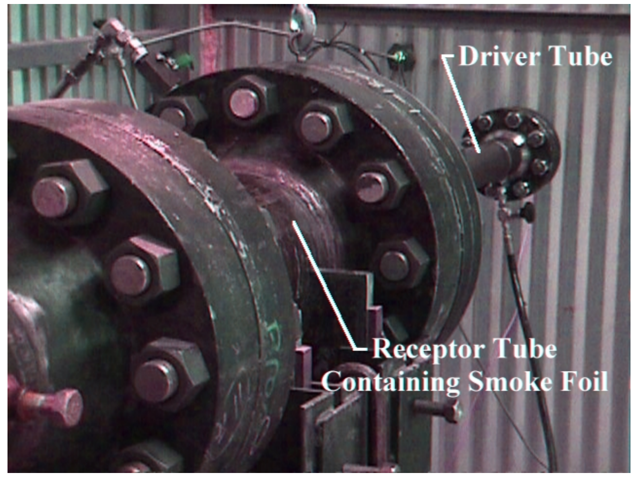

Figure 3. Experimental setup used to determine the critical conditions for transmission from a fuel-oxygen driver to a confined fuel-air receptor gas.

Having obtained the critical mixture composition, the corresponding critical tube diameter, d_c, for that mixture was then determined from the critical tube data and correlations reported by Moen et al. [13]. The driver effectiveness, β_1, can then be defined by $\beta_1 = d_c/D_0$ where D_0 is again the driver tube diameter. A similar approach was adopted in an earlier study [6] to quantify the effectiveness of orifice plates and tube bundles at enhancing transmission. Defined in this manner, higher values of β_1 signify more effective driver tubes. Values of β_1 have been included in Table I. The critical value, $\beta_1^* = 3.37$ (by interpolation), means that an equimolar C_2H_2-O_2 driver is capable of initiating an unconfined C_2H_2-air detonation even though it is 3.37 times smaller than the critical tube diameter for that mixture.

Using the above results as a baseline, a second trial series was conducted to quantify the influence of the

Table II

Pre-detonator Trials: Effect of Confinement for Equimolar C_2H_2-O_2 driver tubes

Trial Number	**Driver/Receptor Tube Diameters (cm)**	**Receptor Gas %C_2H_2-air**	**Result**	**Confinement Effectiveness $\beta_2 = d_c/d_c^0$**	**Overall Effectiveness $\beta = \beta_1^* \times \beta_2$**
60-00	7.62 / 20.3*	6.00	Multi-head Detonation	1.08	3.64
61-00	7.62 / 20.3*	6.00	Multi-head Detonation	1.08	3.64
62-00	7.62 / 20.3*	5.75	Multi-head Detonation	1.29	4.35
03-01	7.37 / 21.6**	5.50	Multi-head Detonation	1.58	5.32
04-01	7.37 / 21.6**	5.00	Multi-head Detonation	2.58	8.69
05-01	7.37 / 21.6**	4.50	Multi-head Detonation	4.83	16.3
07-01	7.37 / 21.6**	4.25	Multi-head Detonation	7.09	23.9
08-01	7.37 / 21.6**	4.125	Spinning	8.75	29.5
06-01	7.37 / 21.6**	4.00	Single-head Spin	11.0	37.0

* denotes field trial; ** denotes laboratory trial

receptor tube walls on the transmission process. Preliminary experiments were carried out using the apparatus shown in Figure 2, but with a 20.3-cm diameter, coaxially-aligned, pipe positioned downstream of the driver tube exit. However, the majority of tests were performed in the laboratory apparatus shown in Figure 3. It consisted of a closed receptor vessel 21.6-cm inside diameter by 6.1 metres long and having three interchangeable driver tubes of 5.08, 7.37, and 10.2 cm inside diameter. A smoke foil 0.66 metres in length and covering the full periphery of the receptor was positioned downstream of the driver tube exit to capture the details of the reinitiation process. All tubes were fitted with pressure transducers. In these tests, the fuel-air mixture was prepared in the receptor vessel by the method of partial pressures, using a water manometer to meter the fuel, and it was recirculated with a pump to guarantee homogeneity. The driver gas was prepared in the same manner as for the earlier trials.

Table II summarizes the available results at the time of writing for an equimolar acetylene-oxygen driver of 7.37-cm diameter. It can be seen that successful initiation of a cellular detonation in the fuel-air mixture was possible for acetylene concentrations as low as 4.25% versus a critical concentration of 6.13% in the absence of confinement. Spinning detonation waves were observed for lower acetylene concentrations suggesting that the mixture is close to its lean detonability limit. Included in Table II are the confinement effectiveness factors defined by $\beta_2 = d_c/d_c^0$ where d_c is once again the critical tube diameter for the fuel-air mixture tested and d_c^0 is the corresponding critical diameter for the base case of no confinement. The overall transmission effectiveness is then given by $\beta = \beta_1^* \times \beta_2$. It can be seen in the table that the conditions present in Trial 07-01 resulted in an overall transmission effectiveness approaching 24 (i.e., 3.37 x 7.09), a very impressive performance gain over the case of transmission of C_2H_2-air detonation from a tube to an unconfined region.

CONCLUSIONS

The preliminary results of this study have shown that both the power of the driver tube mixture and the confinement provided by the receptor tube walls play an important role in determining the overall effectiveness of detonation transmission from a pre-detonator to the main combustion chamber of a PDE. In particular, an equimolar C_2H_2-O_2 mixture is found to be more effective than a stoichiometric mixture because of its higher detonation velocity. For the base case of no confinement, such a driver can successfully initiate an unconfined C_2H_2-air detonation even though it is 3.37 times smaller than the critical tube diameter for that mixture. The confinement offered by the receptor tube walls further enhances the transmission process. For driver and receptor tube diameters of 7.37 cm and 21.6 cm, respectively, successful transmission of detonation to the C_2H_2-air mixture was possible using a driver tube approximately 24 times smaller than the critical tube diameter for the receptor gas. Tests are currently in progress for other values of D/D_0 for both stoichiometric and equimolar acetylene-oxygen mixtures. Results will also be obtained for propane-oxygen initiating propane-air as this fuel is a suitable gaseous simulant for the more practical JP-10 fuel.

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